

# **Testing of the Autonomous Microconductivity-Temperature Vehicle and a Direct Technique for the Determination of Turbulent Fluxes with Autonomous Underwater Vehicles**

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## **LONG-TERM GOAL**

Our long-term goal is to measure the horizontal variability of heat and salt flux in the upper ocean. This will allow us to study the turbulent boundary layer under non homogeneous forcing and the development of coherent boundary layer features such as rolls and Langmuir circulation.

## **OBJECTIVES**

Our immediate objectives are to develop a technique to measure vertical water velocity and the turbulent fluxes of heat and salt with Autonomous Underwater Vehicles (AUV), and to construct a vehicle to fully test and exploit the technique. We have done this in a limited way with our Autonomous Conductivity and Temperature Vehicle (Morison and McPhee, 1997). We use the vertical motion of the ACTV as a proxy for the vertical motion of the water through which it moves. Comparison with other measurement techniques indicates this produces reasonable estimates of flux at the scales of convective turbulence. The key elements of the new technique will be to use all available guidance and control data and account for the dynamics of the vehicle in the estimation of vertical velocity. A new small AUV will be built for proving the technique. The new AUV is crucial for this because it will have an adequate sensor suite to fully measure the vehicle motion, and its configuration and control system will be optimally designed to determine vertical velocity.

## **APPROACH**

The new technique for determining vertical velocity is based on Kalman filtering (Gelb, 1974). It satisfies the requirements of incorporating all possible sensor data and accounting for vehicle dynamics. The Kalman filter makes an estimate of the state of a dynamic system that is an optimal combination of the modeled response of the system and instantaneous measurements of the system state. The estimates are optimum in a weighted least square sense, with the weighting dependent on the estimated measurement error and forcing variance. The filter is recursive, i.e., the estimates depend only on present measurements and the estimate at a preceding time. As such, a filter only runs forward in time and can indeed be used in real time. The analysis of vehicle data can be done after all data are collected. In such a case the highest accuracy is obtained by running a Kalman filter forward and backward in time over the data in a process called Kalman smoothing.

The first issue in developing the smoothing technique is deriving a system model. The second issue is estimating the measurement errors and the forcing variance. The derived model and error estimates

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are then used in the Kalman smoothing technique to estimate vertical water velocity. These can be combined with vehicle measurements of temperature and salinity to determine heat and salt fluxes.

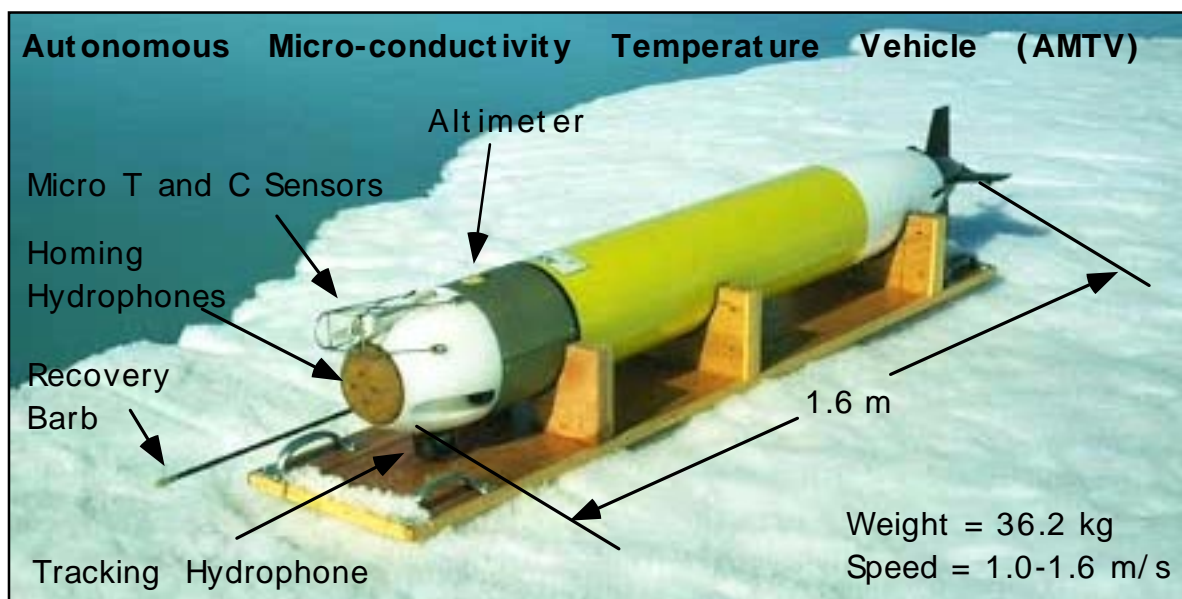
The new technique was first developed for use on existing ACTV data and then applied to analyze data from the new Autonomous Micro-conductivity Temperature Vehicle (AMTV). The AMTV was designed to take full advantage of the new analysis technique. It is based on the Woods Hole Oceanographic Institution's Remotely operated Underwater measurement System (REMUS). Micro-conductivity and micro-temperature sensors are added for heat and salt flux determination. Test runs in local waters are used to verify the new vehicle model used in the smoothing procedure. Test runs under Arctic ice are combined with simultaneous measurements of turbulence with fixed sensors to test the Kalman results.

## WORK COMPLETED

Over the past year we have completed testing of the Kalman smoothing method on the ACTV data, taken delivery of a REMUS vehicle from Woods Hole, modified it to make the AMTV, derived a new model of the AMTV, tested the vehicle in local waters and at the SHEBA ice station, and applied the Kalman smoothing technique to samples of the data.

The Kalman smoothing software was developed in the prior year of this grant. Testing of the Kalman smoothing method on ACTV data was completed this year. It provided improvement over the simpler methods used in Morison et al. (1998), and demonstrated the potential of the technique. However, the performance was limited by the relatively simple instrumentation of the ACTV. The results were presented at the 1998 Ocean Sciences meeting by Hayes and Morison (1998).

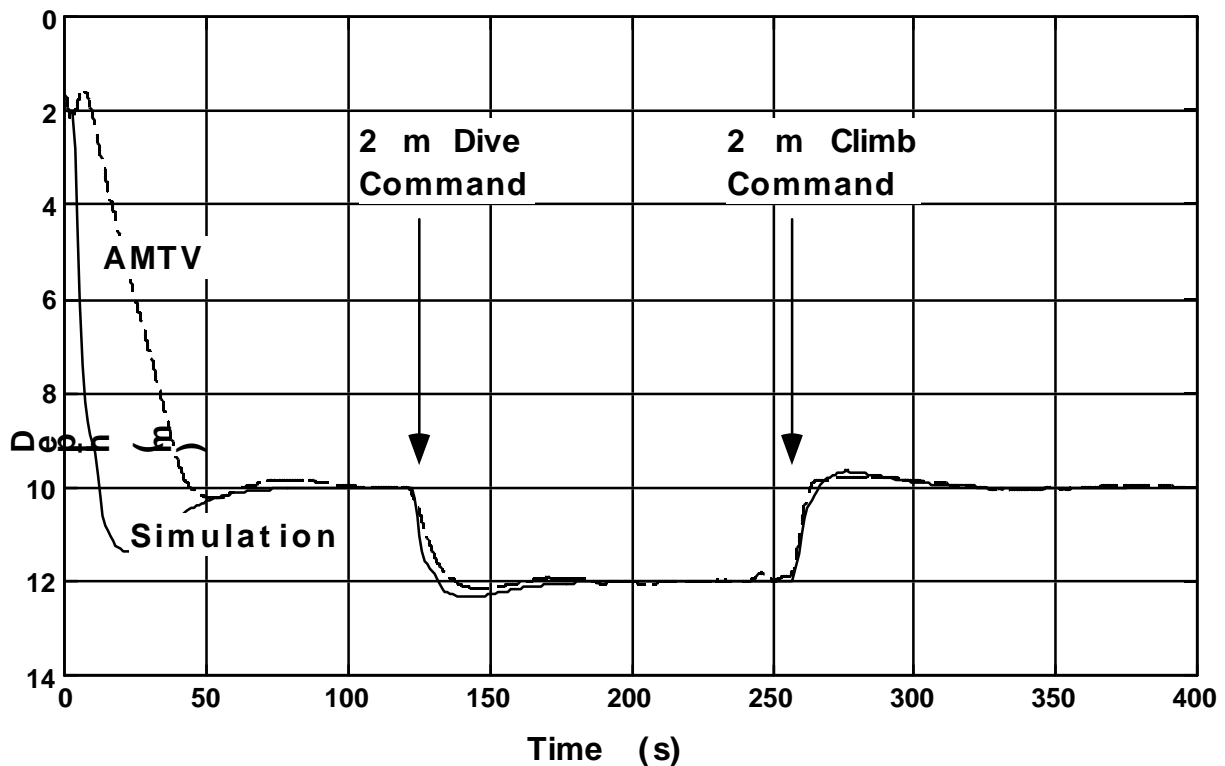
We took delivery of the REMUS vehicle in September 1997 from the Ocean Systems Lab (OSL) at Woods Hole. We completed significant design work, fabrication, and software development in order to convert it to the AMTV (Figure 1). These efforts included,



*Figure 1. The AMTV during testing at the SHEBA Ice Station, August 1998.*

lengthening the dry hull section for new electronics and sensors, and installing a flooded hull section carrying the Tritech sonar altimeter and the Sea-Bird micro-conductivity and temperature probes. In addition to the REMUS hardware, the extended dry hull section includes new electronics for micro-conductivity and temperature signal conditioning, new instrumentation power conditioning and control, a 16-bit A/D converter board, and a hard disk drive data storage system. New hardware was developed to make the vehicle suitable for tracking and recovery in an under-ice environment. This included a synchronous transponder for use with our portable acoustic tracking range. To increase the vehicle state measurements available for the determination of vertical velocity, a Systron Donner Motion Pack inertial reference unit was installed. It contains solid-state pitch, roll, and yaw rate sensors and a three-axis accelerometer package. A sensitive Paroscientific pressure sensor was also installed. These instruments allow the optimum measurement of motion for a vehicle of this size. A substantial effort was also devoted to new software for instrumentation data acquisition and for tracking, homing, and recovery modes of operation. We also developed new ancillary hardware for under-ice launch and recovery.

Testing of the AMTV was first carried out in the fresh water of Portage Bay in Seattle. The basic systems were checked out and various problems were corrected. Stability tests indicated the vehicle was stable with the Woods Hole supplied control software. However, perhaps due to the addition of our hull section, various control parameters had to be modified to produce good response in both pitch and yaw. The testing and modification of the control system were done in concert with development and testing of the vehicle model for the Kalman smoother. The model was developed from the ACTV model but required various modifications to account for the different vehicle configuration. Further testing was performed in Puget Sound from the APL research vessel *Miller*. Long runs were made there, larger depth excursions were performed, and the acoustic tracking, navigation, and homing systems were tested. Emphasis was placed on validation of the vehicle model by testing the vehicle response to step-change depth commands. Figure 2 shows such a comparison. In this comparison the vehicle dives more slowly than simulated, especially during the initial dive to 10 m, because the vehicle reached a limit on maximum pitch angle in the vehicle control system. This limit is not approached in level runs of the vehicle used for turbulence measurements and is not included in the linear model. Away from this limit, such as during the climb at 260 s, the character and time scale of the model and vehicle responses match well.



**Figure 2. AMTV model simulation compared to AMTV test run in Puget Sound. The depth response of the model and the vehicle to 2 m step changes in command depth are shown.**

The ultimate test of the Kalman smoothing method required operation of the vehicle in a natural planetary boundary layer in the presence of reliable fixed-point turbulence measurements. This was done by taking the AMTV to the SHEBA ice station in July and August 1998. There we operated the AMTV under various ice conditions in and around leads of various sizes. The runs were initiated from a point adjacent to a portable turbulence mast belonging to Miles McPhee. The mast provided fixed point measurements of turbulent velocity, temperature, and conductivity at one or two depths. These provide data for comparison to the AMTV measurements. As one might expect with taking a new vehicle in the field, there were numerous technical problems, but we were able to overcome them. We made about 50 AMTV runs under various ice types and open water. The total amount of run track is about 70 km. These statistics exceed the similar statistics for the whole ACTV program (3 Arctic field experiments and excluding lake runs). All but a few recoveries were in-the-net captures. The AMTV sonar altimeter, besides providing useful scientific data, helped in the safe operation of the vehicle as well. Runs could be made at substantial depth to map the ice under a particular run track. Then subsequent runs could be made as close as possible to the ice for turbulence measurements. In addition to the AMTV, we used the ROV to get high resolution CTD, ice draft, and video very close to the ice. In the strong stratification conditions of summer, these data are important to understanding the ice ocean conditions in which we were operating.

## RESULTS

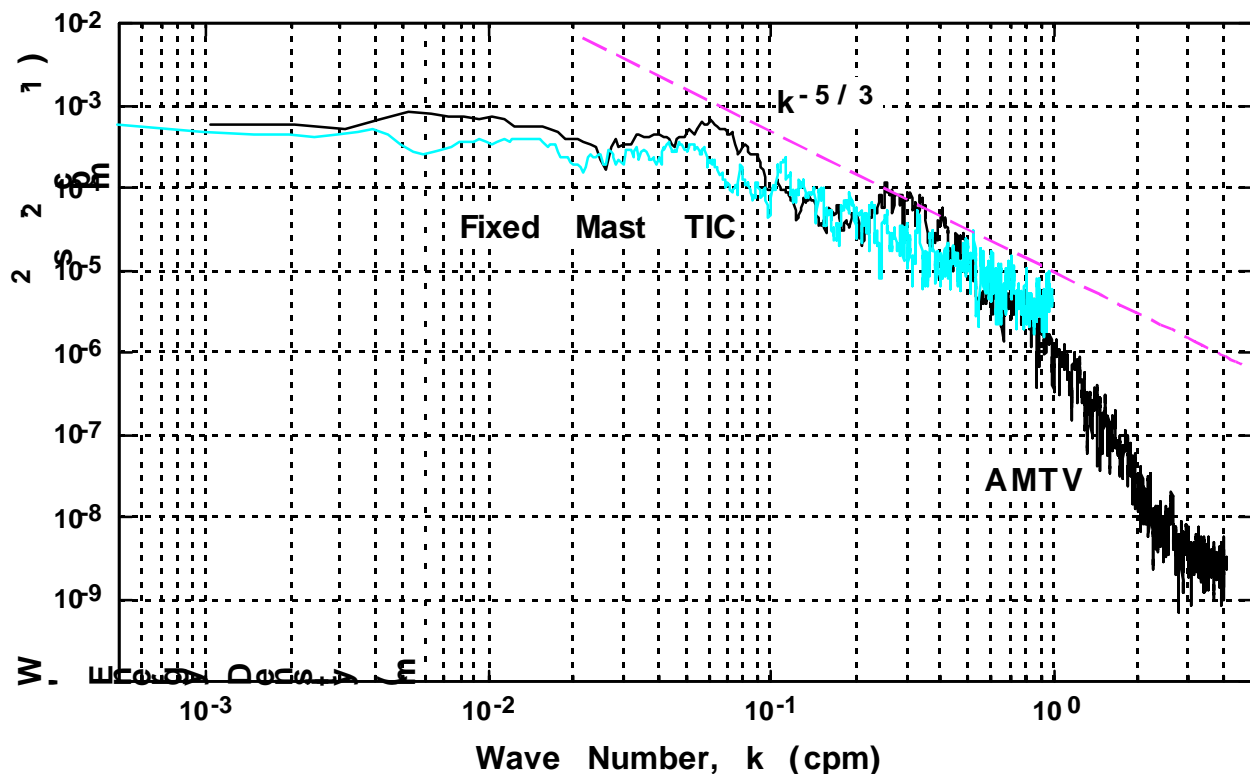
The data quality from the SHEBA test is quite good. The micro-temperature records are very clean and show distinct patterns under various lead conditions. There appears some irregularity in the transfer function of the signal conditioning circuit, but we will determine this through bench testing and correct for it in our signal processing. The micro-conductivity gave some drift and noise problems, but the turbulence spectra look very good. We can use familiar processing procedures for eliminating the drift

and noise problems. The AMTV sonar altimeter data are excellent. They give a high resolution of ice draft with virtually no noise. This has made it easy to see the relation between changes in temperature and salinity structure and ice conditions. We see patterns of temperature and vehicle motion related to lead geometry, so we are optimistic we can relate turbulent fluxes to surface processes.

Since returning from SHEBA we have applied the Kalman smoothing technique to a sample of the data. So far we have used depth and pitch angle as the measured variables and the AMTV model developed before the SHEBA test. We have not fully exploited all the new instrumentation. Even so, the results are excellent. Figure 3 shows comparison spectra of vertical velocity estimated from the AMTV with the Kalman smoothing technique and vertical velocity measured directly with Miles McPhee's Turbulence Instrument Cluster (TIC). The TIC was at 5 m depth at the edge of a large lead. The vehicle data is from a leg of a run at 5 m upstream of the TIC under the lead. Both spectra show approximate agreement with the  $k^{-5/3}$  spectral slope characteristic of turbulence. The most impressive feature of the AMTV spectrum is that it agrees with the fixed mast spectra out to  $k = 0.5$  cpm, dropping below the TIC spectrum above that frequency. This cutoff wave number corresponds to a wavelength (2 m) nearly equal to the theoretical minimum equal to the length of the vehicle (1.6 m). The improvement of the result over the ACTV results appears to be due largely to vastly improved performance of the AMTV pressure sensor. The only worrisome difference is the extra AMTV energy in a band around  $k = 0.3$  cpm. This may be due to a subtle resonance in the vehicle. We are optimistic that use of more of the inertial sensors will improve estimates in this band.

## **IMPACT/APPLICATION**

The fundamental impact of this research will be to provide a technique whereby nearly any AUV can provide turbulence data as a side benefit to other sampling it carries out. This is because the proposed technique requires only data from a vehicle's on board motion sensors. Used with simple vehicles, the technique will yield spatial maps of turbulent energy. Used with sophisticated AUVs, the technique will also yield spatial maps of vertical fluxes of the other variables being measured. Such maps will be the key to identifying dynamically critical areas of the Autonomous Ocean Sampling Networks (AOSN) sampling regions and will be crucial to determining the budgets of heat, salt, biomass and pollutants.



*Figure 3. Spectra of vertical velocity from fixed-mast Turbulence Instrument Cluster and from Kalman smoothing of the AMTV data. Data for both were gathered at the SHEBA lead site, August 7, 1998.*

## TRANSITIONS

Vehicles like the AMTV and the analysis method we are developing could be used militarily. We visualize such AUVs making clandestine surveys of littoral areas. The method of extracting information on water motion from vehicle motion would have application in determining the wave energy in areas of planned amphibious assault. The technique may also find application as a non-acoustic detection and tracking tool. This would find application in "smart" and acoustically quiet weapons that could detect the wakes of vessels and follow them. Torpedoes using the technique in real time could conceivably follow turbulent ship wakes to their targets.

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